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TEMPERATURE OF MARS.

A DETERMINATION OF THE SOLAR HEAT RECEIVED.

By Percival Lowell.

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Heat hitherto deduced from Distance only.

Up to the present time the chief obstacle to crediting Mars with the possibility of life has lain in accounting for sufficient heat on the surface of the planet. So far the determination of this heat has been limited to a consideration of distance from the sun. Thus Professor Young, who feels the difficulty acutely, says in his "General Astronomy":[1] "We know that on account of the planet's distance from the Sun the intensity of solar radiation upon its surface must be less than here in the ratio of 1^2 to 1524^2." For the resulting temperature he seems to have assumed either with Newton, that a body radiates heat in direct proportion to its temperature, which would give for the mean temperature of Mars 223.6° Abs. (−236°F.), or Dulong and Petit's law, which would make it 363° Abs., or −96° F.; for he entertains the possibility that the polar caps may be composed of solid carbonic acid, which freezes only at −109° F.

A better determination has recently been made by Moulton by taking Stefan's law of radiation, that of the fourth power of the temperature. Stefan's formula is not only the best experimentally to-day, but has since its enunciation been deduced from theoretic considerations by both Boltzmann and Galitzine. On this basis the mean temperature comes out −33° F., the reasoning being this: If a body remains at the same temperature, it must radiate as much heat as it receives. Consequently the temperature is as the fourth root of the amount received. Absolute zero is minus 459° F. The mean temperature of the earth is usually taken at 60° F. Therefore, to determine the mean temperature of Mars we have, calling x its temperature on the absolute scale, the following equation:

$$x : 518 \text{ Abs.} :: \sqrt[4]{4} : \sqrt[4]{9},$$

which gives −33° F. for the mean temperature of the planet.

[1] Ed. 1898, p. 363.

Distance but One of Several Factors.

In these and similar determinations, the only thing considered is the distance from the sun, as if the surfaces of the planets were immaterial points in space, and the whole heat arriving there went to warm the bodies. But such is far from being the fact. Not only are the surfaces material, but any air the bodies possess as a covering is material too. Now, postponing for the moment consideration of the blanketing effect of air, the actual amount of heat received at the surfaces in consequence of their constitution or of their air-envelope, is not at all what mere distance would lead one to infer.

Division of Radiant Energy.

So soon as a radiant ray strikes matter it suffers division of its energy. Part of it is reflected, part absorbed, and part transmitted. What is reflected is sent off again into space, performing no work in the way of heating the body. Now the amount reflected is not the same in all cases, depending for its proportion upon the character of the matter the ray strikes.

If the surface of a planet be itself exposed unblanketed by air, the absorbed and transmitted portions go to heat the planet, directly or indirectly.

If the planet be surrounded by air, the portion transmitted by this air, plus what is radiated or reflected from it to the solid surface, must first be considered. Then, upon this quota as a basis, must secondly be determined how much the surface in its turn reflects. The balance alone goes to warm the ground or ocean.

Light and Heat.

Radiant energy is light, heat, or actinism, merely according to the effect we take note of. If our eyes were sensitive equally to all wavelengths, we could gauge the amount of heat received by a body by the amount of light it reflected, — that is, by its intrinsic brightness, or albedo. For this percentage deducted from unity would leave the percentage of heat received. This procedure may still be applied, provided account be also taken of the heat depletion suffered by the invisible rays. Two problems, then, confront us.

We must find the albedoes of the several planets in order to compare one with another in its reception of heat, and we must find the relation borne by the visible and invisible rays to the subject. The latter problem may best be attacked first.

Actinometers and pyrheliometers are instruments for measuring *in toto* the heat received from the sun; and they have been used by

Violle, Crova, Hansky, and others to the determination of this quantity at given places, and so to a conclusion as to the amount of heat outside our air, or the Solar Constant. Langley's great contribution to the subject was the pointing out that the several wave-lengths of the different rays were not of homogeneous action or modification, and that to an exact determination of the Solar Constant it is necessary to consider the action of each separately, and then to sum them together. To this end he invented his spectro-bolometer.

By means of this instrument Langley mapped the solar radiation to an extension of the heat spectrum unsuspected before. He then carried it up Mt. Whitney in California, and discovered two important facts: one, that the loss in the visible part of the spectrum was much greater, not only actually, but relatively to the rest, than had been supposed; and the other, that the greater the altitude at which the observations were made, the larger the value obtained for the Solar Constant. Both of these are pertinent to our present inquiry.

With a rock-salt prism, instead of a glass one, he next extended still farther the limits of the heat spectrum toward the red, the effect of the solar radiation proving not negligible as far as $\lambda = 15\ \mu$.

In 1901 Professor Very, who had been his assistant earlier, published an important memoir on the Solar Constant, based upon these bolometric observations, but with a value for it got from spectral curves derived from simultaneous actinometric and bolometric determinations at Camp Whitney and Lone Pine, and extended from them outside the atmosphere by taking both air and dust effects into account in selectively reflecting and diffracting the energy waves. The air effect is proportionate to the air mass, but the dust effect increases in greater ratio as one nears the surface of the ground. The formulæ he used were adaptations of those by Rayleigh for accounting for the selective reflection and diffraction of small particles.[2]

Energy of Visible and Invisible Spectrum.

Planimetrical measurement of the area enclosed by the curve deduced for outside our atmosphere gives the following results:

Distribution of Heat in the Spectrum.

	Wave-lengths.	Percentage.
Invisible,	$\lambda = 0.2\ \mu$–$0.393\ \mu$	2.5
Visible,	$\lambda = 0.393\ \mu$–$0.76\ \mu$	32.
Invisible,	$\lambda = 0.76\ \mu$–$15\ \mu$	65.5
		100.

[2] U. S. Department of Agriculture, Weather Bureau, No. 254.

giving for the

Visible portion,	32 per cent,
Invisible "	68 "

of the whole.

Loss of Heat in Traverse of the Air.

Turning, now, from the question of the initial heat for different parts of the spectrum at the time the solar radiation enters the air, we come next to consider the loss the several rays sustain in their traverse of it.

From Very's curves for the radiation at the confines of the atmosphere at Camp Whitney and at Lone Pine, 18 $\lambda = 1.2\ \mu$, we get the amount transmitted at these two stations, employing planimetric measurement as before, and introducing with him the absorption in the red and infra-red from the Alleghany measures, which he considers the same at Lone Pine.

From Very's measures we have, calling the whole heat at the confines of the atmosphere unity, —

Transmission.

	$\lambda = 0.2\ \mu$–$1.2\ \mu$.	$\lambda = 1.2\ \mu$–$15\ \mu$.
Outside	50.	50.
Camp Whitney . . .	31.3	
Lone Pine	24.3	25.1

To get that for sea-level we shall take Crova's actinometric measures at Montpellier (height 40 m.), made on August 13, 1888; at $12^h\ 30^m$, under a barometer of 761 mm. Simultaneously with these, other self-registering ones were taken by him on Mt. Ventoux (height 2000 m.). The respective calories he obtained were, —

	Montpellier.	Mt. Ventoux.
Aug. 13, $12^h\ 30^m$, 1888.	0.975 calories, bar. 761.1 mm.	1.360 calories, bar. 613.5 mm.

We shall reduce these to the same scale as the Lone Pine results, made with the pyrheliometer and used by Very, to wit :

	Lone Pine.
Aug. 11, 12, 14, 12^h–$12^h\ 30^m$, 1881.	1.533 calories, bar. 663 mm.

giving for

Montpellier.	Mt. Ventoux.
1.180 calories.	1.643 calories.

This value of 1.180 is one which is probably about the average of clear days in our latitude, the day in question being registered by Crova as "very clear."

From these several data we find the following values for the solar radiation received at the respective posts, in calories in one column, in percentage of that entering the atmosphere in another.

SOLAR RADIATION.

	Bar.	Calories.	Percentage.
Outside the atmosphere .	0.	3.127	1.000
Camp Whitney	500 mm.	1.896	.606
Lone Pine	663 "	1.533	.490
Montpellier	761 "	1.180	.377

The loss in the visible spectrum is almost wholly from selective or general reflection and from diffraction, that in the invisible one from selective absorption. The absorptive loss by bands in the former is only about 1 per cent of the whole, and the loss by reflection in the latter probably not over 7 per cent of its depletion.

In view of the fact that the absorption is known to take place high up in the air, Very adopted the Alleghany amount for Lone Pine, the difference being insensible; but when it comes to Camp Whitney it is clear from the above that 9 per cent of it is got rid of, between $\lambda = 1.2\ \mu$ and $= 10\ \mu$ by rising the 11,700 ft. from sea-level.

DEPLETION IN VISIBLE RAYS.

We may now find the depletion in the visible part of the spectrum which is not in general the same as that for the invisible part, decreasing relatively with the altitude and reversely increasing as the air envelope becomes thicker. It does this at a greater rate than the increase of the air mass, because the particles suspended in the air, dust, water globules, and ice augment more rapidly than the air mass as one approaches the ground.

Drawing the curve for transmission at the sea-level on the same principles as those for outside the atmosphere at Camp Whitney and at Lone Pine, and then measuring the amounts of transmission of each within the limits of the visual rays, from $\lambda = 0.393\ \mu$ the K line to $\lambda = 0.76\ \mu$ the A band, we get the following table :

TRANSMISSION OF SOLAR RADIATION IN THE VISIBLE SPECTRUM.

	Calories received from the Whole Spectrum.	Visible Portion transmitted.
Outside the atmosphere	3.127	1.000
Camp Whitney	1.896	.664
Lone Pine	1.533	.482
Sea-Level	1.180	.210

The relative loss in the regions I, $\lambda = 0.393\ \mu$ to $\lambda = 0.76\ \mu$, and II, $\lambda = 0.76\ \mu$ to $\lambda = 1.2\ \mu$, between the several stations is as follows:

	I.	II.
Outside to Camp Whitney . .	0.105	0.029
Camp Whitney to Lone Pine . .	0.055	0.010
Lone Pine to Sea-Level . . .	0.086	0.027

LIGHT RECEIVED FROM THE DAY SKY.

To these transmissions must be added that part of the solar radiation which is lost by reflection and diffraction in the atmosphere before reaching the ground, but is reflected again upon it, causing the brightness of the day sky. This amount is sufficient to obliterate the stars. Compared with direct sunlight, its ratio as determined by Langley[3] is

	Sun.	Sky.
Illumination	80	19

or 24 per cent of the sun's light.

We must therefore increase the energy transmitted by 24 per cent of itself. This gives finally:

	Transmission.		Portions reflected into Space.
Outside	1.000	1000	0
Sea-Level	.21	26	74

ALBEDO OF THE EARTH.

Now the fraction of the incident energy in the visible spectrum is that by which we see the body and is called its albedo. The albedo of our air, then, comes out .74. To get the whole albedo of the earth we must add to it the albedo of the surface.

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[3] Professional Papers of the Signal Service, Vol. 15.

The albedo of various rocks and of the ocean is as follows:

White quartzite . .	.25	Dark slate .	.09
Clay shale	.16	Ocean . .	.075

For forest we may perhaps take .07
and snow according to purity .50 — .78

The percentages of distribution of surfaces being about

Ocean .	72 per cent	Steppes & Desert .	10 per cent
Forest .	10 per cent	Polar Caps . . .	6 per cent,

we deduce 11 for the albedo of the surface. But this being illuminated by only 25 per cent of the light outside the air gives about 3 for its quota to the planet's illumination. When finally the earth's whole albedo to one viewing it from space becomes $.74 + .3 = .77$ albedo of the earth for a clear sky.

As the earth's is about 50 per cent cloud-covered (see the researches of Teisserinc de Bord on Nebulosity) and the albedo of cloud is .72, we get .75 for the mean albedo of the earth.

Value of Loss of Light a Minimal One.

That the value above found for the percentage transmission of solar radiation to the earth's surface is a maximal rather than a minimal amount, and the albedo a minimal rather than a maximal one, is hinted by the fact that the higher the observer ascends above the surface the greater his estimate of the solar constant becomes. Thus Langley in his memoir on the Mt. Whitney expedition says:

"In accordance with the results of previous observers, then, and of our own with other instruments, *we find a larger value for the Solar Constant as we deduce it from observations through a smaller air mass.*" The italics are his.[4]

Depletion by Water-vapor on Mars.

We are now in position to estimate the heat actually received respectively at the surfaces of Mars and the earth. The visual part of the spectrum containing 32 per cent of the incident solar radiation gives us its quota directly from the albedo, since the heat received = 1 albedo. The infra-red portion containing 65 per cent of the whole depends upon the character of the air and of what it holds in suspension.

[4] Researches on Solar Heat, p. 68.

The greater bulk of the depletion in this part of the spectrum comes from the absorption by water-vapor, water itself, or ice and carbon dioxide. At the earth's surface the transmission in consequence is about 50 per cent; at Camp Whitney it was about 59 per cent. We might, therefore, suppose it still greater through the air of Mars, which is very thin, and if we did so we should find a still larger fraction of solar heat to be received by the planet's surface; so that such a supposition would actually increase the cogency of the present argument. But the very thinness of the air joined to the lesser gravity at the surface of the planet would lower the boiling point of water, as investigation shows (see later in the paper) to something like 110° F. The sublimation at lower temperatures would be correspondingly increased. Consequently the amount of water-vapor in the Martian air must on that score be relatively greater than in our own.

Depletion by Carbon Dioxide.

Carbon dioxide, because of its greater specific gravity, would also be in relatively greater amount, so far as this cause is considered. For the planet would part, *caeteris paribus*, with its lighter gases the quickest. Whence, as regards both water-vapor and carbon dioxide we have reason to think them in relatively greater quantity than in our own air at corresponding barometric pressure. We may therefore assume provisionally that the absorption due this cause is what it is with us at Camp Whitney, or about 40 per cent of the whole, leaving 60 per cent of the heat transmitted.

It is distinctly to be noted not only that this estimate lowers the determination of the heat received at the surface of Mars, but that what is thus lost in reception goes to make the retention of the heat received all the greater.

Albedoes of the Planets.

The albedoes of the several planets, according to the determinations latest obtained, those by Müller at Potsdam, together with that found above for the earth and for the moon by Zöllner, stand thus:

Mercury	.17	Jupiter	.75	(using Struve's latest diametral measures, .78)
Venus	.92	Saturn	.88	
Earth	.75	Uranus	.73	
Moon	.17 (Zöllner)	Neptune	.63	
Mars	.27			

Heat received by Earth and Mars.

We will now apply the argument from the albedo.

Heat received at the Surfaces of Mars and the Earth.

	Per cent of Whole Energy.	Per cent of Heat received to Whole Energy. Mars.	Earth.
Visual spectrum . . .	32	73	23
Infra-red	65	60	50
Total		64	41.5

The ultra-violet rays slightly increase the depletion by selective dispersion for both planets, and probably the more for Mars.

Insolation.

But this is not all. The above deduction applies only to such sky as is clear. Now the earth is cloud-covered to the extent of 50 per cent of its surface on the average; Mars, except for about six Martian weeks, at the time of the melting of the polar cap and over an area extending some fifteen degrees from the pole, stands perpetually unveiled. The surface thus fog-enveloped is 0.034 of its hemisphere, and the time 0.23 per cent of the half year, whence the total ratio of cloud to clear the whole year through over the whole surface is less than 1 per cent.

The albedo of cloud being .72, its transmission, including absorption re-given out, cannot exceed .28, and may be taken as 20.[5] Consequently the effective heat received on this score by the earth is about as $20 \times 50 = 60$ per cent, and for Mars 99 per cent, giving the ratio that of .60 to .99.

Taking now Stefan's law that the radiation of a body is as the fourth power of its temperature, and remembering that, since the two planets maintain their respective mean annual temperatures, they must radiate as much heat as they receive, we have the following equation from which to find the mean annual temperature of Mars, x, in which $459.4^\circ + 60^\circ$ or 519.4°F. on the absolute scale denotes the mean annual temperature of the earth:

$$x : 519.4^\circ :: \sqrt[4]{1^2 \times .64 \times .99} : \sqrt[4]{1.524^2 \times .415 \times .60}$$

or

$$x = 519.4^\circ \tfrac{892}{872}$$

giving

$$x = 531.4^\circ \text{ Abs.} = 72^\circ \text{ F. or } 22^\circ \text{ C.}$$

[5] This agrees with Arrhenius' estimate of the heat transmissibility of cloud.

Heat received and Heat retained.

Such, then, would be the mean annual temperature of the planet, were the heat retained as well there as here. I am far from saying that such is the temperature. For the retention is not the same on the two planets, being, on account of its denser air, much better on the earth. But that such is the amount received is enough to suggest very different ideas as to the climatic warmth from those hitherto entertained.

Temperature deduced from Heat retained.

To obtain some idea of the heat retained and of the temperature in consequence we may proceed in this way:

Let y = the radiant energy received at the surface of the earth.
y_1 = that similarly received on Mars.
e = the relative emissivity or the coefficient of radiation from the surface of the earth, giving the ratio of the loss in twenty-four hours to the amount received in the same time, due to factors other than the transmissibility of the air, which is separately considered.
e_1 = the same coefficient for Mars.

Clouds transmit approximately 20 per cent of the heat reaching them; a clear sky at sea-level, 50 per cent. Consequently as the sky is half the time cloudy the mean transmission of its air-envelope for the earth is

$$.35\, e$$

For Mars it is

$$.60\, e_1$$

To get, then, the mean temperature of the planet in degrees, x, from the heat retained, which is the daily mean receipt less the mean loss, we have the following equation, the mean temperature of the earth being [519.4°F. Abs.] 288°C. above absolute zero:

$$\frac{x}{288.5} = \frac{\sqrt[4]{y_1\,(1 - .60\, e_1)}}{\sqrt[4]{y\;(1 - .35\, e)}}$$

Determination of e.

To find e we have the data that the fall in temperature toward morning on the earth under a clear night sky is about 18° F. or 10° C.;

under a cloudy one, about 7° F. or 4° C. Taking the average day temperature from these data at 292°Abs. on the centigrade scale or 19°C., and considering an average day sky and a clear night, we have the transmission or loss

$$\tfrac{1}{2}\,(.35 + .50)\,e \text{ or } .425\,e\,;$$

while for an average day and a cloudy night it is

$$\tfrac{1}{2}\,(.35 + .20)\,e \text{ or } .275\,e$$

We form the following equation to determine e:

$$\frac{292^\circ - 10^\circ}{292^\circ - 4^\circ} = \frac{\sqrt[4]{y\,(1 - .425\,e)}}{\sqrt[4]{y\,(1 - .275\,e)}}$$

whence $$e = .47$$

Since the radiation by day is greater by about 1.15 than by night

being as $$\frac{292^4}{282^4},$$

we have more approximately

$$\tfrac{1}{2}\,(.40 + .50)\,e \text{ or } .45\,e$$

for a clear night and average day and

$$\tfrac{1}{2}\,(.40 + .20)\,e \text{ or } .30\,e$$

for a cloudy night under the same conditions.

This gives, $$e = .4634,$$

or substantially what it was before. It changes the final result for the mean temperature of Mars by less than two tenths of a degree.

Determination of e_1.

Since in the mean the planet radiates as much heat as it receives and

$$\frac{y_1}{y} = 1.10$$

the radiation must be in the same ratio. Whence, the loss by radiation in twenty-four hours on Mars so far as it depends on the heat received is

$$\begin{aligned} e_1 &= 1.1\,e \\ &= .51, \end{aligned}$$

or by the more approximate calculation in the paragraph above, it still

$$= .51$$

Substituting these values in our equation (page 660), we find x, the mean temperature of Mars,

$$\begin{aligned} &= 8^\circ.7\text{ C.} \\ \text{or } &= 47^\circ.7\text{ F.}, \end{aligned}$$

taking into account the heat radiated away as well as the heat received and gauging the temperature by the heat retained; by the net, instead of the gross, amount of the radiant energy received.

If we assume clouds to transmit less heat than 20 per cent, we diminish y and increase $(1 - .35\,e)$, so that the ultimate result is not greatly altered.

If we take Arrhenius' formula for the temperature T of the earth's surface as affected by the air-envelope, we have as determined in his paper on the effect of carbon dioxide in the air:

$$T^4 = \frac{\alpha A + M + (1-\alpha)\,A\,(1+\nu) + N\left(1 + \frac{1}{\nu}\right)}{\gamma\,(1 + \nu - \beta\nu)},$$

where α = atmospheric absorption for solar heat,
β = atmospheric absorption for earth-surface heat,
A = Solar Constant, less loss by selective reflection by the air,
M = heat conveyed to the air from other points,
N = heat conveyed to the surface from other points,
$\nu = 1$ — albedo of the surface,
γ = radiation constant.

The values for these quantities found bolometrically for a clear sky are $\alpha = .50$,
$A = 1 - .79 \times .32 = .747$ = whole spectrum — albedo of the air × visible portion,
$\beta = \alpha$ approximately,
$\nu = 1 - .11 = .89$

For the earth in its entirety $M = \delta$ and $N = o$, since what is lost by convection in one place is gained in another.

Applying this same formula to the case of Mars we have similarly —

$\alpha_1 = .40$ approximately,

$$A_1 = \frac{1^2}{1.524^2}(1 - .17 \times .32) = \text{whole spectrum} - \text{albedo of its air} \times \text{visible portion}$$

$$= \frac{.946}{1.524^2}$$

$\beta_1 = \alpha_1$ approximately.

$\nu_1 = 1 - .13 = .87$

Whence for the earth under a clear sky

$$T^4 = \frac{A\,(1 + \nu - \nu\alpha)}{\gamma(1 + \nu - \beta\nu)},$$

and similarly for Mars, substituting its values for A, α, and β.

Since in both $\alpha = \beta$ and $\gamma_1 = \gamma$ approximately, we have T_1 for Mars, which gives

$$\frac{T_1^4}{T^4} = \frac{A_1}{A}.$$

But the earth is .50 cloud-covered, and the transmission of cloud being not more than .20 (the value he takes), we have finally

$$\frac{T_1^4}{T} = \frac{A_1}{A}\frac{.99}{.60},$$

whence

$$T_1 = .974\ T,$$

and T being 519.4° Abs. on the Fahrenheit,

$$T_1 = 505.7°, \quad \text{that is,} \quad 46.3°\ \text{F. or } 8°\ \text{C.}$$

a result substantially the same as we have deduced.

Had we assumed β to be .70 and to be in like proportion to α for Mars, we should have had

$$T^4 = 1.140\,\frac{A}{\gamma}$$

and

$$T_1^4 = 1.101\,\frac{A_1}{\gamma_1},$$

which gives not far from what we had before, since it lowers the resulting temperature for Mars by only about 4° F. or 2° C.

Albedo and Air.

Some interesting conclusions follow on the investigation of planetary albedo.

If we classify the various planets according to their atmospheric envelopes, we shall discover a significance in their several albedoes. Three classes stand forth distinct: 1. those possessing no air; 2. those with air but wholly or in part cloudless; 3. those with a cloud covering. Into these classes the planets fall in the manner below, while the albedoes they respectively present are placed alongside of them.

		Albedo.
I. Airless Bodies.		
Mercury		.17
Moon		.17
II. Air-enveloped Bodies.		
Venus, Cloudless	Medium air	.92
Earth, 50 % Cloudless	Medium air	.77
Mars, Cloudless, thin air		.27

	Albedo.	
III. Cloud-canopied Bodies.		
Jupiter	.75	or .78 by Struve's latest measures.
Saturn	.88	or .78 by Struve's latest measures.
Uranus	.73	
Neptune	.63	

The albedo of cloud is .72. Whence it is clear that cloud cannot account for the albedo of Venus, but that it accords with the albedo of the four major planets. That an air-envelope increases the albedo of a planet is witnessed first by the greater brilliancy per unit of disk of the earth, Venus, and Mars as compared with the airless bodies, Mercury and the Moon, and secondly, by the relative specific brightness of Venus and Mars, together with what has above been found as to that of the earth. It appears that the denser the air surrounding the planet the more dazzling the aspect the planet presents. This is undoubtedly due not to the gases themselves, but to the solid or liquid particles the gases support in the shape of dust, ice-particles, or drops of water.

This testimony of the albedo that Venus is not cloud-covered but atmosphere-hid is corroborative of the observations made by me at

Flagstaff, 1896, and at Mexico in 1897, from which it appeared that the planet's markings were not obscured by cloud, but seen, as it were, through a veil, and which also showed the correctness of Schiaparelli's deduction that Venus in all probability turned in perpetuity the same face to the sun. That she did so was evident from the long-continued observations at Flagstaff and Mexico. Now such a facing always of one hemisphere sunward would cause convection currents upward in the centre of the disk, and an indraught along its edge, together with an absence of moisture on the sunlit half of the planet. Dry winds of the sort blowing over a perpetual Sahara must be laden with dust, which Very's investigation finds to be the chief cause of reflection in our own air. The high albedo of Venus thus stands accounted for.

Light around Venus.

A sidelight bearing on the albedo of air comes from the prolongation of the crescent of Venus when the planet passes in inferior conjunction before the sun.

It used to be thought that the fine circlet of light that then crowns the disk was due to refraction in the Venusian air. But in 1898 Russell, at Princeton, showed that it is rather reflection from that air than refraction through it which reaches our eyes. Now that such should be the case follows from the planet's albedo, if that albedo be of atmospheric and not of nubial origin. This supports the conclusion reached by the visual observations of Venus at Flagstaff. For refraction means transmission, and if the air of Venus reflects 90 per cent of the incident light, it can refract but 10 per cent at most. The light from it, therefore, must be reflected, not refracted, light in the proportion of nine to one. The albedo, Russell's observations, and the Flagstaff results, thus all concur to the conclusion that Venus is not enveloped in cloud.

Deduction as to Amount of Martian Air.

Another outcome of the consideration of albedoes is a means it gives of approximating to the density of the Martian air. Mars is chiefly Saharan, and dust, therefore, must be largely present in its air. Now from the albedo of various rocks, of forests, and of other superficies, we may calculate the relative quotas in the whole albedo of Mars, of its surface and its air. Five eighths of its surface is desert, and therefore of an albedo of about .16, as its hue shows three eighths of a blue-green, the color of vegetation, with an albedo of about .7, while one sixth is more or less permanently of a glistening white in the

polar caps. These would combine to give it an albedo of .13. This, however, is illuminated by so much of the light as penetrates the atmosphere only, about three quarters of the whole. Whence the apparent albedo of the surface must be about .10. As the total albedo of the planet is .27, the remaining .17 is the albedo of its air.

Taking the density of the air as proportionate to its brilliancy, which would seem to be something like the fact, since the denser the air the more dust it would buoy up, we have for the Martian air a density about two ninths our own over each square unit of surface.

Now, if the original mass of air on each planet was as its own mass, we should have for the ratio between the Earth and Mars, 9.3 of atmosphere on the former to 1 on the latter. This being distributed as their surfaces, which are in the proportion of 7919^2 to 4220^2, must be divided by 3.5, giving 2.7 times as much air for the earth per unit of surface. The difference between 2.7 and 4.5 found above may perhaps be attributed to the loss of air Mars has since suffered on the supposition of proportionate masses to start with.

Air Density at Surface of Mars.

To get the relative density of the air at the surfaces of the two planets these amounts must be divided by the ratio of gravity at the surfaces of the two, that is, by .38.

For the density being proportional to its own increase, if D denote the density at any point, we have

$$dD = -Dg dx,$$

where g denotes the force of gravity at the surface of the earth, and x is reckoned from that surface outward into space, whence

$$D = Ae^{-gx},$$

A being the density at the surface of the planet.

For Mars we have correspondingly

$$D_1 = A_1 e^{-g_1 x}.$$

For the whole mass of air over a space $dydz$ we have, for the Earth,

$$\int_0^\infty D dx = -\frac{A}{g} e^{-gx} \Big|_{x=0}^{x=\infty} = \frac{A}{g}.$$

Similarly for Mars it is

$$\frac{A_1}{g_1};$$

and as the whole mass of the earth's atmosphere over any space $dydz =$ 4.5 that of Mars at a similar point, and $g_1 = .38g$, we have

$$\frac{A}{1} = 4.5\,\frac{A_1}{.38},$$

whence as $A = 30$ inches of barometic pressure, $A_1 = 2.5$ inches.

Boiling Point on Mars.

Owing to the less amount of the Martian air and the smaller gravity at the surface of the planet the boiling point of water is greatly reduced, being probably in the neighborhood of one hundred and eleven degrees Fahrenheit. If the whole mass of air be $\frac{1}{4.5}$ of the earth's, while gravity is .38 of ours, the pressure is

$$M_1 g_1 = .09 \text{ of the earth's},$$

whence the boiling point is 44° C. or

$$79 + 32 = 111° \text{ F.}$$

For the same reason sublimation takes place more freely at identical temperatures there. Proportionally, therefore, there would be more water-vapor in the air.

We may summarize the results for Mars :

Mean Temperature	48° F. or 9° C.
Boiling point of water	111° F. or 44° C.
Amount of air per unit surface .	7 in. or 177 mm. ; $\frac{2}{9}$ of the earth's.
Density of air at surface . . .	2.5 in. or 63 mm. ; $\frac{1}{12}$ of " "

The look of the surface entirely corroborates the temperature result of this investigation.

January 14, 1907.